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Major efforts of this project fall into four categories: (1) investigations were performed on the relationship between the dimensionality of a dataset and its underlying cognitive processes; (2) two approaches for diagnosing erroneous rules of operation were developed (an "error vector" system for constructing error diagnostic programs for signed-number arithmetic and fraction addition problems, and a series of logical statements for constructing diagnostic programs for fraction problems); (3) to circumvent the problems encountered in the construction of error diagnostic programs, two indices based on deterministic Guttman theory were formed and used to detect aberrant response patterns; and (4) the necessity for dealing quantitatively with variations in errors and changing rules of operation led to the investigation of probabilistic models for error diagnosis based on item response theory. (Author/PN)

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FINAL REPORT:

DIMENSIONALITY, SCORING AND RELATED PROBLEMS IN ADAPTIVE TESTING

PART 1

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Abstract

Major efforts of the project fall into four categories.

1) Investigations were performed on the relationship between the dimensionality of a dataset and its underlying cognitive processes. The datasets represent the computational arithmetic domains of addition and subtraction of signed numbers and fractions. Error diagnostic computer programs for these computational skills written on the PLATO® system were used for examining each student's procedural rule. Various analyses imply that the systematic application of erroneous rules by many students causes multidimensionality of the data.

2) Two approaches for diagnosing erroneous rules of operation were developed; an "error vector" system for constructing error diagnostic programs for signed-number arithmetic and fraction addition problems, and a series of logical statements for constructing diagnostic programs for fraction problems. A series of experimental data collected between 1979-1982 revealed that the rate of diagnosing erroneous rules by these deterministic approaches becomes very low (about 50%) when learning is most active. Hence, it is impossible to help students with prescriptive information from these error diagnostic systems. Moreover, developing such computer programs in general areas will be painstaking and time-consuming.

3) To circumvent the problems encountered in the construction of error diagnostic programs, two indices based on deterministic Guttman theory were formed and used to detect aberrant response patterns. The first of these indices was useful in categorizing erroneous rules into serious or less-serious errors. The second index proved to be very powerful for detecting erroneous rules resulting from the students' misconceptions. In several different datasets of arithmetic computations, the detection rates were always higher than 95% of the erroneous rules which had been diagnosed separately by the error vector system.

4) The necessity for dealing quantitatively with variations in errors and changing rules of operation led to the investigation of probabalistic models for error diagnosis based on item response theory. A group of extended caution indices was formulated. These indices have a prominent mathematical feature and some functional similarities to both of the other indices; however, used traditionally, their detection rate for some of the most frequent erroneous rules is unexpectedly low. As an alternative approach, the concept of "rule space" was developed. All responses, both correct and erroneous, are decomposed into components, which are mapped into a vector space spanned by the true scores and one of the standardized extended caution indices (ECI4z). A pattern classification technique is used to separate each rule from its neighboring points in the rule space. Since the ECI4z is a continuous function, those points which plot close to a rule represent responses yielded by "slips" or random errors, or by imperfect applications of the rule.

DIMENSIONALITY

One of the first goals of the project was to address the problem of multidimensionality of achievement test data. Latent trait theory provides a potentially powerful tool for locating a person's ability or achievement level within a hierarchical set of test items; however, latent trait models require that test data be unidimensional (i.e., that they measure a single trait). On the other hand, achievement test data usually are multidimensional, so that difficulties were anticipated in the application of latent trait theory to the diagnosis of student errors on achievement tests.

Several datasets were collected from seventh and eighth grade students taking computerized tests on the PLATO^{R} system during 1979 - 1980, while five datasets were simulated on the PLATO^{R} computer. All datasets were based on test results within the domain of signed-number arithmetic. Tatsuoka, et al. (Tatsuoka & Baillie, 1982a; Tatsuoka, et al., 1982) developed "SIGNBUG", a set of computer programs on the PLATO^{R} system which analyze each student's procedural rules for solving signed-number arithmetic problems.

These data were used in several experiments which investigated the relationship between the dimensionality of a dataset and the cognitive processes which led to the student's solution of the problems. One study examined the dimensionality of an achievement test across different learning stages under two different instructional methods (Tatsuoka, 1981). This study demonstrated that different instructional methods affect the dimensionality of test scores to a large extent. The results also indicate that in the early stages of learning, students tend to use their rules of operation inconsistently during the test. This causes a

clear violation of the local independence assumption, which is essential to latent trait theory.

A second study compared the dimensionality of achievement test scores based only on correct answers, to scores based on whether the student used the correct algorithm (Birenbaum & Tatsuoka, 1980, 1983). Results indicate that in achievement data based on a specific arithmetic problem-solving domain, the factorial structure of the data is strongly affected when a variety of different algorithms underlie the student responses, with a resulting increase in the dimensionality of the data. The fact that students may get right answers by following a wrong rule is reflected in the psychometric properties of the test. When the conventional scoring system is used, it results in negative correlations among some items, and increased dimensionality; when the scoring system takes into consideration the thought processes of the student, there is a reduction in dimensionality and considerably higher correlations among the tasks, without changing their mean values.

The simulated data referred to above were used as a means to control the number of algorithms underlying the responses, in order to study the effect on dimensionality of the test data when the number of algorithms increases (Birenbaum & Tatsuoka, 1982). This simulation was meant to describe a situation in which 25% of the subjects knew nothing about the topic being tested, merely guessing randomly for the answers, while another 25% had mastered the tasks and answered all of the items correctly. The remaining half of the subjects were presumed to have mastered incorrect rules. The number of incorrect algorithms was increased with each successive dataset; one in the first, two in the

second, up to five in the fifth, distributed in each set in equal proportions. In order to make the effect of the algorithms clearer, a hypothetical situation was simulated in which 75% of the responses were consistent, i.e., each subject used the same rule consistently throughout the test. A principal components analysis of these data demonstrated that an increase in the number of wrong algorithms results in a decrease in both the reliability coefficients and in the amount of variance accounted for by the first factor. A similar analysis of real data collected before and after instruction, as well as for two kinds of instruction, indicated less heterogeneity of the underlying algorithms (i.e., fewer wrong rules) after instruction than before, regardless of the kind of instruction.

Two mathematical methods for extracting unidimensional subsets from multidimensional datasets were investigated. An algorithm based on graph theory efficiently extracted nonredundant chains of items using a series of matrix manipulations performed on the dominance matrix (Yamamoto & Wise, 1980), and an order-analysis procedure was used successfully to isolate uni-dimensional item subsets in both real and simulated data (Wise, 1981).

ERROR DIAGNOSIS

Two methods were developed for diagnosing erroneous rules of operation. In the first of these, a system of binary error vectors was generated from item responses (Tatsuoka, et al., 1980). Operations in signed number addition were decomposed into sign and absolute value components, and each component was represented by a vector of binary numbers accounting for all

possible operations for doing the problem. By a process of elementwise multiplication of the set of error vectors, a particular wrong rule can be determined uniquely, provided the student consistently uses that rule.

The second method for diagnosing erroneous rules consisted in the derivation of a series of logical statements to be used for constructing error-diagnostic programs. Klein, et al. (1981),) described and illustrated a procedure for constructing error-diagnostic items for addition and subtraction of fractions, based on a procedural network. This approach is too complex to be practical, and the need for defining a hierarchy of item difficulty was recognized.

Tatsuoka and Tatsuoka (1981b) described a system of order analysis that was developed by Takeya (1981), called item relation structure analysis, and used it for examining the structural relations among a set of 24 items in addition and subtraction of fractions. The goal was to devise a technique for investigating the item structure with respect to the roles of each item in determining the student's misconceptions. Results were inconclusive, though promising, and the need for further study was indicated.

Standiford, et al. (1982), described a procedural network for solving problems in decimal fraction addition and subtraction, and compared the item dominance predicted from this network with that predicted from the item relations structure analysis model. In general, the latter model confirmed item dominance patterns predicted by the former.

Chevalaz and Tatsuoka (1983) described and compared two order analytic techniques for analyzing the structure of a test. Ordering theory of Krus and Bart (1974), and the item relation structure analysis method proposed by Tatsuoka and Tatsuoka (1981b) were used to extract the hierarchical

item structure from three datasets. It was found that the Krus and Bart procedure more adequately represented the complex interrelationships among test data, but that use of the item relation structure analysis appears to be more appropriate when the data contains many errors.

As part of the effort to identify and catalog specific erroneous rules, Shaw, et al. (1982), analyzed results of a written test in fraction addition, and interviewed many of the students. Their report describes the test performance of 26 students who displayed a variety of erroneous rules. The cases were selected for their potential usefulness in designing and implementing an error-diagnostic testing system and in designing appropriate remediation.

Tatsuoka (1981) attempted to quantify the relative seriousness of errors in signed number addition problems. All component procedures for carrying out the addition problems properly were expressed by a hierarchical tree. Then, each erroneous rule was characterized by assigning two quantities, representing what and how many steps were followed to produce the responses. If a rule were the result of a misconception at an earlier level in the network, then it was more likely committed by students in the early stage of learning, or by lower ability students. For students nearing mastery, any erroneous rules would be due to mistakes from the latter part of the procedural network. A procedural steps conformity index was designed to express quantitatively both single and compound error sources. The need for further work in generalizing these procedures was recognized.

Using the same error classification system, Tatsuoka (1984) divided 27 erroneous rules of signed-number addition problems into two groups.

non-serious (A) and serious (B) error types, in order to investigate changes over time in their rate of incidence. Forty-five subjects from junior high school took a test in signed-number addition, which was administered six times at various stages of instruction over a period of a year and a half. Those students whose verbal ability as measured by the Stanford Verbal Test fell in the top 16% also were identified. Results showed (1) use of the right rule decreased over the first three tests, then increased dramatically; (2) use of A-type rules did not change much, while use of B-type rules decreased slowly over time; (3) on the second test students with high verbal ability used A-type rules much more than the more serious B-type, but the reverse was true for the other students. The latter finding suggests that students with high verbal ability may be less likely to adopt the more serious error types in the early stages of learning.

Tatsuoka and Birenbaum (1981) reported the observed effects on test performance resulting from differences in instructional backgrounds. An adaptive diagnostic test was used as an integral part of an instructional program in signed-number arithmetic on the PLATO^{R} system. The testing procedure worked well for most examinees, but not for those who had been exposed to a different conceptual framework prior to the PLATO^{R} instruction. Differences in prior and subsequent instructional methods affected the learning of more advanced materials and produced lower achievement scores on the posttest given at the end of the program. These results present a serious problem when students are to be routed to an instructional level based only on performance on a diagnostic test. It is important to examine the conceptual basis for both stages of instruction and to route each examinee accordingly.

The two methods for diagnosing errors referred to above are both deterministic; therefore, their rate of diagnosis diminishes if students apply their rules inconsistently. Analysis of data gathered during 1979-1980 (Birenbaum & Tatsuoka, 1981; Tatsuoka, 1983a) confirmed that (1) students tend to change their rules of operation most during the early stages of learning, and (2) the rate of diagnosis decreases accordingly, to as low as 50%. Since this is precisely the learning stage when diagnosis is most needed, it is impossible to help students with prescriptive information from these error-diagnostic systems. Furthermore, the creation of computer programs for error vector systems and process networks is too complex and time-consuming for general applications.

NORM CONFORMITY AND INDIVIDUAL CONSISTENCY INDICES

Since the usefulness of the error diagnostic programs is seriously limited when students change their rules of operation, a method for detecting such changes seemed useful. Accordingly, two indices were developed for measuring the degree of conformity or consistency of an individual examinee's response pattern on a set of items (Tatsuoka & Tatsuoka, 1980; 1981a; 1982a; 1983). The first, called the norm conformity index (NCI), measures the proximity of the pattern to a baseline pattern in which all 0's precede all 1's when the items are arranged in some prescribed order. The second, called the individual consistency index (ICI), measures the extent to which an individual's response pattern remains invariant when he or she responds to several waves of parallel items. Both of these indices were developed originally as potential tools

for assisting in the extraction of subsamples of examinees for whom the data are uni-dimensional or nearly so.

The NCI is a sort of backward extension to the individual level of one of Cliff's group consistency indices. Its calculation requires that the test items be rearranged in the order of difficulty for some particular group. The NCI turned out not to be very useful for the originally intended purpose of extracting unidimensional subgroups. Rather, it was found to be more useful in highlighting the different response patterns that are typical of individuals with different instructional backgrounds, and in categorizing erroneous rules by degree of seriousness.

The ICI depends on the task difficulties as determined by an individual student's state of knowledge. Its definition calls for the existence of two or more parallel subtests. Calculation of the ICI is the same as that for the NCI, except that the items are arranged in the order of difficulty of the skill types for the particular individual instead of the order of difficulty for a group. The unique feature of the ICI is that its values are individually oriented and free from group dependence.

The ICI was found to be quite useful for identifying individuals who could be removed from a sample to improve the approximation to unidimensionality exhibited by the data matrix of the remaining group. The ICI value is large when an individual responds to similar items in the same way. A small ICI value indicates uncertain or random responses. A combination of high ICI and low total score indicates consistent errors, while a combination of low ICI and low total score suggests that the student does not have a clear method for proceeding and is answering at random or by trial and error.

Application of the ICI, together with the total scores, to several of the signed number arithmetic datasets detected most (over 95%) of the erroneous rules which had been detected separately by the error vector diagnostic system.

Although the ICI is useful in detecting aberrant response patterns resulting from the use of wrong algorithms, it requires repeated measures in a test. Therefore, the index is not applicable to many commercial achievement tests or to criterion referenced tests designed to measure the outcome of treatments in a wide range of content areas. However, when tests are aimed at assessing the progress of a student's learning and used as an integral part of instruction, the information obtained from the ICI will be useful for assessing how well the student understands the subject.

EXTENDED CAUTION INDICES AND RULE SPACE

The necessity for dealing quantitatively with variations in errors and changing rules of operation led to the investigation of probabalistic models for error diagnosis based on item response theory. Indices of the degree to which an individual's pattern of responses is unusual were classified into two general types: (1) those that use item response theory and (2) those that rely on observed item responses and standard summary statistics based on those responses. Tatsuoka and Linn (1981, 1983) demonstrated a link between these two approaches by showing a correspondence between the S-P curve theory developed by Sato, and test response curves and group response curves developed from item response theory. Furthermore, the caution index defined in Sato's S-P curve theory, which is based on

a comparison of observed item responses to group responses, was extended to theory-based estimates of person and group response probabilities. That is, S-P curve theory and the caution index, which originally were developed within a discrete domain of 0-1 scoring, were extended to a more general case of probabilities.

Five extended caution indices were defined, designated respectively the ECI1, ECI2, ECI3, ECI4, and ECI5. These indices are linear transformations of the covariance of a person's response pattern with one of two theoretical curves computed using item response theory (i.e., the group response curve for the ECI1, ECI2 and ECI3, or the person response curve for the ECI4 and ECI5).

The ECI4 is similar to the individual consistency index, or ICI (see above). The ICI was shown to be useful in detecting a variety of erroneous rules of operation with signed-number addition and subtraction problems, but its application is limited because it requires repeated measures within a test. The ECI4 not only avoids the repeated measures limitation but it also is effective for identifying persons who consistently use an erroneous rule in answering signed-number arithmetic problems. Based on its application to a set of achievement test data, the ECI4 distinguishes persons who are consistently using erroneous rules from those who are not, provided that these erroneous rules are not popular in the data used for estimating item and person parameters. Therefore, selection of the correct data set for estimating these paramaters is very important when applying these indices.

Tatsuoka and Tatsuoka (1982a) investigated the statistical properties of the ECI1, ECI2 and ECI4. They found that both the ECI1 and ECI2 have

the constant expectation of zero, regardless of the level of the person parameter θ_i, while the expectation of the ECI4 is a function of θ_i.

As was shown with data from a 40-item signed number subtraction test, the conditional variances of the three ECIs under consideration have U-shapes, with inflated values at both the extremely high and extremely low true scores and fairly constant values in between. In order to avoid this weakness, the ECI1, ECI2, and ECI4 were standardized by subtracting the conditional expectation of each ECI from the original ECI and dividing by the square root of its conditional variance (Harnisch & Tatsuoka, 1983). Goodness-of-fit tests of the standardized ECI's showed that they fit normal distributions well.

Since all of the extended caution indices are based on conditional probability of θ_i, they do not allow a fair comparison of two values if they are obtained from examinees at two different ability levels. However, since the standardized ECI's do not depend on θ_i, two standardized ECI values obtained from different θ_i values are comparable in terms of the extent of anomaly they signify.

The use of the various ECI's for detection of erroneous rules proved to be unexpectedly low in all cases (about 60%). Although the reasons for this are not entirely clear, it appears that if an otherwise normal dataset includes a considerable number of aberrant response patterns, then such patterns are no longer detectable with high probably by the traditional use of these indices. Investigation of an alternative approach therefore was necessary.

A probabalistic model was developed, called "rule space," in which all responses, both correct and erroneous, are decomposed into component

parts and mapped as points in a geometric space (Tatsuoka, 1983a, 1983b; Tatsuoka & Baillie, 1982b). Rule space is defined as the cartesian product of the estimated true scores and the values of the standardized extended caution index ECI4z (Tatsuoka & Baillie, 1982b). In other words, rule space is a geometric representation of the rules used by the student. In this space, the erroneous rules resulting from the same kind of misconception cluster closely, as was confirmed by results plotted from several datasets.

The advantage of using the standardized extended caution index ECI4z is its effectiveness for separating clusters of responses from one another. If two response patterns from the same θ level differ they will be plotted at different locations in the rule space. Furthermore, the degree of unusualness of a response is represented by its distance from the true-score axis. A cluster of response patterns consists of the response pattern yielded by some rule and its "slips," due to partially consistent application of the rule. Using pattern classification to separate the clusters in the rule space accounts for variability of errors in the model (Tatsuoka, 1982b). By calculating a set of linear classification functions of the various clusters and by setting boundaries to divide the regions, it is possible to identify the underlying misconception of a new response with some probability of error by examining in which region the new response falls. Thus, the problem of diagnosing an individual student's misconceptions has been transmuted into a classification problem. Using the probabilistic approach of rule space and pattern classification for the diagnosing of errors promises to remedy the weaknesses of deterministic methods without losing their strengths.

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